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Leveraging Open-Source Power Measurement Standard Solution

Genesis of a new power measurement initiative

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Problem Statement

- Power Management optimization is key for power-hungry battery-operated devices
  - Who never had to complain about its phone / smart watch / connected device not able to keep up a single day?
- But the community have limited power measurements equipment
  - Community boards (and even custom dev. boards) poorly designed for power measurements
    - Missing shunt resistors / probe points on key power rails
  - Expensive high-precision lab equipment
  - Existing low-cost solutions but with limited performances (i.e. accuracy)
  - No standard power measurement connector
- Risks:
  - Merging patches hurting device power consumption
  - Limited possibilities for hobbyists to provide/contribute to power-optimized open-source solutions
- The community needed a high-perf low-cost standard solution for power measurements

Menu of the Day

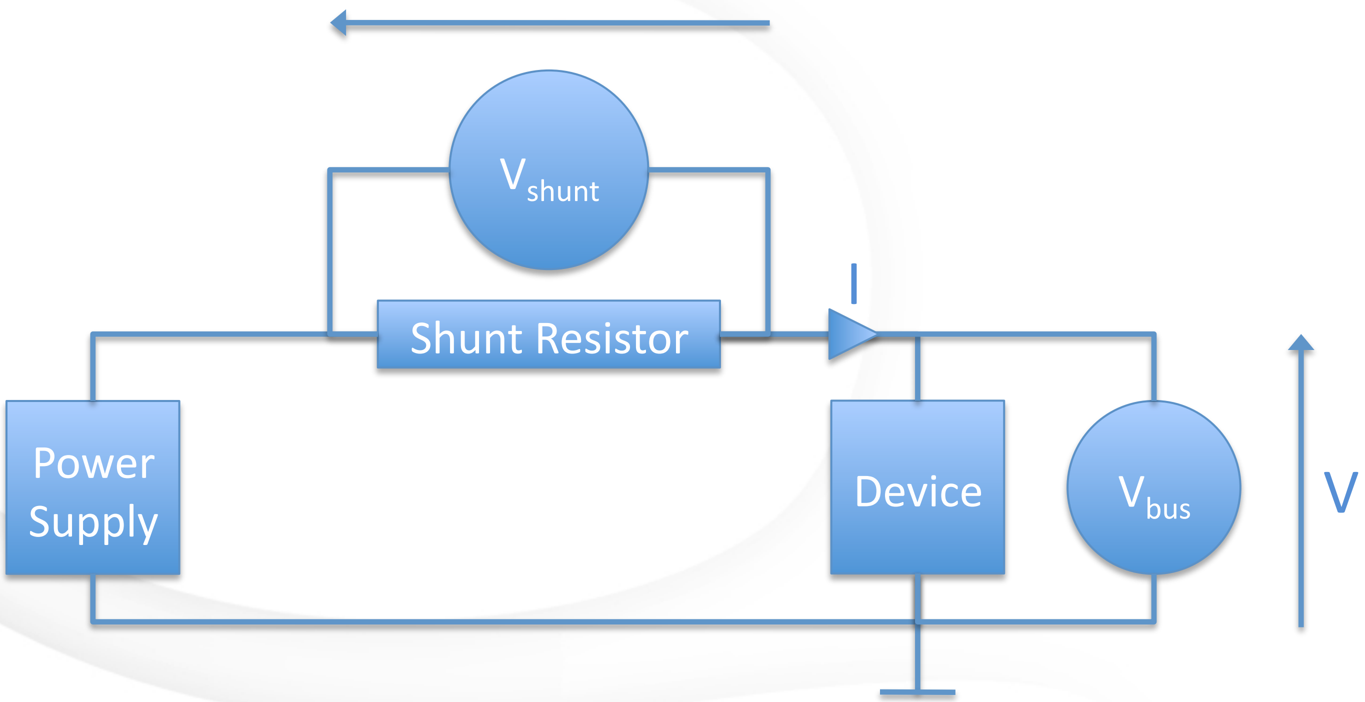
- Power Measurement Basics
  - Board Requirements
  - ADC resolution
  - Shunt Resistor selection
- The “ACME” Initiative
  - Rationale
- Demo
- Q & A

Power Measurement Basics

Test points, ADC resolution, Sampling Rates, Shunt Resistor selection, ...

Power Measurement Technique (1)

- To measure power, both voltage and current have to be measured.
  - P (Watt) = U (Volt) * I (Ampere)



Power Measurement Technique (2)

- To measure the supply voltage:
  - No extra onboard component required, but only 2 test points (Vdd + gnd) at current sink (e.g. SoC) ends.

- To measure the current consumption:
  - An additional shunt resistor shall be placed in series with the power line.

  - Following Ohm's law ($U = R * I$, i.e. $I = V_{shunt} / R_{shunt}$), by measuring the voltage drop at the resistor ends and knowing the resistor value, the current can be calculated.

  - Accurate current measurement requires high-precision shunt resistor.
    - As per Ohm's law, there is a 1 to 1 ratio between resistor value tolerance and measurement precision.
      - E.g. 5% resistor -> 5% current measurement accuracy, 0.1% resistor -> 0.1% current measurement accuracy
    - Also a very low temperature coefficient variation is required (e.g. 110ppm/℃)

Power Measurement Technique (3)

- The choice of the shunt resistor value is of highest importance
  - Further details in next slides
- Current and voltage are dynamic analog variables.
  - Must be sampled at a sufficient rate (e.g. > 1Ksample/s),
  - Otherwise good amount of consumed energy may be missed => inaccurate measurement
- Voltage and current shall be measured at the same time for proper instantaneous power consumption computation.
- Averaging power consumption of a given amount of [U, I] measurements is done by averaging (U * I).
  - A common error is to average U and I, then compute the $U_{avg} * I_{avg}$
  - $P_{avg} = avg(U * I) != U_{avg} * I_{avg}$

Analog to Digital Conversion (1)

- It is actually all about voltage measurement
  - Current converted to voltage using a shunt resistor (Ohm's law)

- Analog voltage values converted to digital values by ADC (Analog to Digital Conversion) dedicated circuitry

- Some Key parameters in ADC component selection:
  - ADC Min/Max voltage
  - Resolution (8-bit, 12-bit, 16-bit, 24-bit, …)
  - Sampling rate (1Ksample/s, 1Msample/s, …)
  - Minimum offset

Shunt Resistor Selection (1)

- The value of the shunt resistor is dictated by:
  - The ADC voltage range ($V_{shunt_{max}}$, $V_{shunt_{min}}$)
  - The current range to be measured:
    - $R_{shunt} = V_{shunt_{max}} / I_{shunt_{max}}$
  - The acceptable voltage drop supported by the device to be measured:
    - E.g. device requiring 5V ± 5%, then $V_{shunt_{max}} < 250mV$
  - The max. power the resistor can dissipate:
    - $P_{shunt} = R_{shunt} * I^2_{shunt_{max}}$

Shunt Resistor Selection Example (1)

- Example:
  - Conditions:
    - ADC TI INA226:
      - 16-bit ADC,
      - $V_{shunt_{max}}$ = 81,92mV,
      - $V_{shunt_{min}}$ = 2.5uV
    - I_{max} = 1.5A
    - Device operating range: 5V ± 5%
  - Matching shunt resistor:
    - R_{shunt} = 54,6mΩ ≈ 50mΩ
    - P_{shunt} = 0,123W => 1/2W shunt resistor OK
    - $V_{shunt_{max}}$ = 81,92mV < 250mV => within device operating range

Shunt Resistor Selection Example (2)

Shunt Voltage vs Acceptable Drop-Out & INA226 Shunt Voltage Input Range

						INA226 measure range: 10uV to 81,92mV			
					voltage range (V)	0 - 2V	2V - 4V	4V - 5V	5V - 12V
shunt value (ohms)	current range (A)	Contact value (ohms)	Contact drop (V)	shunt power (W)	accepted drop-out (V)	0,05	0,1	0,2	0,5
						shunt voltage (V)			
0,005	5	0,02	0,1	0,125		0,025	0,025	0,025	0,025
0,005	4	0,02	0,08	0,08		0,02	0,02	0,02	0,02
0,005	3	0,02	0,06	0,045		0,015	0,015	0,015	0,015
0,005	2	0,02	0,04	0,02		0,01	0,01	0,01	0,01
0,005	1	0,02	0,02	0,005		0,005	0,005	0,005	0,005
0,005	0,5	0,02	0,01	0,0013		0,0025	0,0025	0,0025	0,0025
0,005	0,25	0,02	0,005	0,0003		0,0013	0,0013	0,0013	0,0013
0,005	0,1	0,02	0,002	5E-05		0,0005	0,0005	0,0005	0,0005
0,005	0,05	0,02	0,001	1E-05		0,0003	0,0003	0,0003	0,0003
0,005	0,01	0,02	0,0002	5E-07		5E-05	5E-05	5E-05	5E-05
0,005	0,001	0,02	2E-05	5E-09		5E-06	5E-06	5E-06	5E-06
0,1	5	0,02	0,1	2,5		0,5	0,5	0,5	0,5
0,1	4	0,02	0,08	1,6		0,4	0,4	0,4	0,4
0,1	3	0,02	0,06	0,9		0,3	0,3	0,3	0,3
0,1	2	0,02	0,04	0,4		0,2	0,2	0,2	0,2
0,1	1	0,02	0,02	0,1		0,1	0,1	0,1	0,1
0,1	0,5	0,02	0,01	0,025		0,05	0,05	0,05	0,05
0,1	0,25	0,02	0,005	0,0063		0,025	0,025	0,025	0,025
0,1	0,1	0,02	0,002	0,001		0,01	0,01	0,01	0,01
0,1	0,05	0,02	0,001	0,0003		0,005	0,005	0,005	0,005
0,1	0,01	0,02	0,0002	1E-05		0,001	0,001	0,001	0,001
0,1	0,001	0,02	2E-05	1E-07		0,0001	0,0001	0,0001	0,0001

Exceed shunt max power (1/2W)

Close to ADC limits

Exceed accepted drop-out

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Assessing Current Measurement Range

- Depending on shunt resistor value and ADC characteristics, different current ranges may be measured
  - With full ADC performance (all ADC bits relevant)
  - With reduced but acceptable performance (not all ADC bits used)

- Example:

  - TI INA226: 16-bit ADC, V_{shunt} = [81,92mV - 2.5uV]
  - Shunt Resistor: 10mΩ / 500mW

  - => optimum range: [0.5A - 5A] (at least 10 bits relevant)
  - => extended range: [1mA - 0.5A] (only 3 to 10 bits relevant)

Current Measurement Range Example

shunt voltage vs ADC precision, INA shunt voltage input range and acceptable drop-out

INA226 measure range: 2,5uV to 81,92mV with 10uVmin

contact value (ohms): 0,013

voltage range (V)	0-2V	2V-4V	4V-5V	/-1:
accepted drop-out (V)	0,05	0,1	0,2	1

shunt voltage precision (V)

input voltage range (V): 0 - 2V

accepted drop-out (V): 0,1

ADC presicion (bit numbers)

shunt value (ohms)	Current value (A)	Power Shunt (W)	shunt voltage (V)	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0,01	16,5	2,7225	0,165		0,041	0,0205	0,0102	0,0051	0,0026	0,0013	0,0006	0,0003	0,0002	8E-05	4E-05	2E-05	1E-05	5E-06	3E-06
	10	1	0,1		0,041	0,0205	0,0102	0,0051	0,0026	0,0013	0,0006	0,0003	0,0002	8E-05	4E-05	2E-05	1E-05	5E-06	3E-06
	5	0,25	0,05		0,041	0,0205	0,0102	0,0051	0,0026	0,0013	0,0006	0,0003	0,0002	8E-05	4E-05	2E-05	1E-05	5E-06	3E-06
	4	0,16	0,04		0,041	0,0205	0,0102	0,0051	0,0026	0,0013	0,0006	0,0003	0,0002	8E-05	4E-05	2E-05	1E-05	5E-06	3E-06
	3	0,09	0,03		0,041	0,0205	0,0102	0,0051	0,0026	0,0013	0,0006	0,0003	0,0002	8E-05	4E-05	2E-05	1E-05	5E-06	3E-06
	2	0,04	0,02		0,041	0,0205	0,0102	0,0051	0,0026	0,0013	0,0006	0,0003	0,0002	8E-05	4E-05	2E-05	1E-05	5E-06	3E-06
	1	0,01	0,01		0,041	0,0205	0,0102	0,0051	0,0026	0,0013	0,0006	0,0003	0,0002	8E-05	4E-05	2E-05	1E-05	5E-06	3E-06
	0,5	0,0025	0,005		0,041	0,0205	0,0102	0,0051	0,0026	0,0013	0,0006	0,0003	0,0002	8E-05	4E-05	2E-05	1E-05	5E-06	3E-06
	0,25	0,000625	0,0025		0,041	0,0205	0,0102	0,0051	0,0026	0,0013	0,0006	0,0003	0,0002	8E-05	4E-05	2E-05	1E-05	5E-06	3E-06
	0,1	0,0001	0,001		0,041	0,0205	0,0102	0,0051	0,0026	0,0013	0,0006	0,0003	0,0002	8E-05	4E-05	2E-05	1E-05	5E-06	3E-06
	0,05	0,000025	0,0005		0,041	0,0205	0,0102	0,0051	0,0026	0,0013	0,0006	0,0003	0,0002	8E-05	4E-05	2E-05	1E-05	5E-06	3E-06
	0,01	0,000001	0,0001		0,041	0,0205	0,0102	0,0051	0,0026	0,0013	0,0006	0,0003	0,0002	8E-05	4E-05	2E-05	1E-05	5E-06	3E-06
	0,001	1E-08	0,00001		0,041	0,0205	0,0102	0,0051	0,0026	0,0013	0,0006	0,0003	0,0002	8E-05	4E-05	2E-05	1E-05	5E-06	3E-06

Always 0

Exceeds accepted drop-out
(considering 13mΩ contact resistance (HE10 connector))

Bits not significant
(voltage close to ADC limits)

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The “ACME” initiative

Another Cute Measurement Equipment

Objectives, key features & decisions, status

ACME Cape: Why?

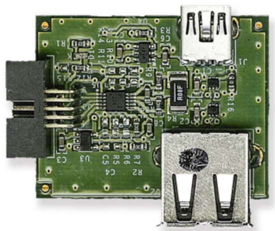
- As power management experts, we used to be frustrated by the existing equipment, either
  - Not matching our needs / not adapted,
  - Windows-only / not Linux-friendly,
  - Proprietary drivers,
  - Limited/ not flexible proprietary application suite,
  - Limited automation capabilities,
  - Too expensive,
  - Too complicated to use,
  - Not accurate enough,
  - Lack of standard power measurement connector (ad hoc solutions only)
  - …

- => We decided to close all these gaps and provide the community with the most flexible low-cost but high-perf solution
  - Challenging, isn't it?! ☺

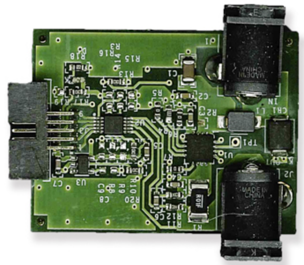
ACME Cape: key requirements

- Main target: hobbyists
- Leverage main community boards
- Current, Voltage, Power, Temperature measurements
- Multi-channel
- Full Open Source SW suite, from drivers up to apps
- Support data post-processing
- Support automation
- Support remote power-switching
- Support USB, Jack power connection
- Support most common embedded devices current range
- Define a standard power measurement connector
- Low-cost / High-perf / Evolutive

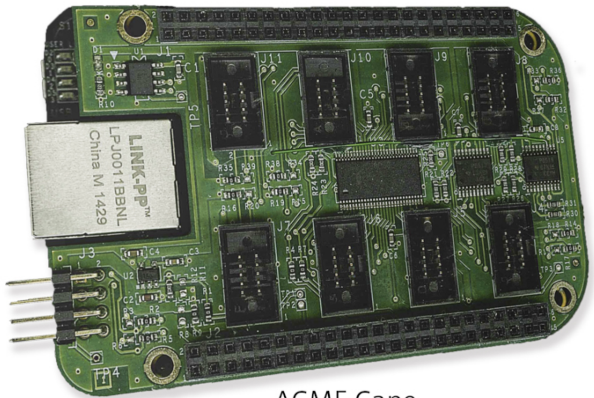
ACME Cape: Here It Is!



USB Power Probe

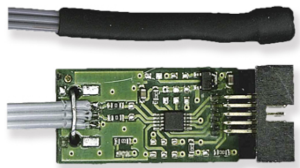


Jack Power Probe

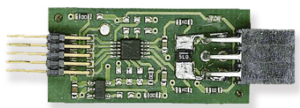


ACME Cape

Temperature Probe



ACME Power Probe



ACME Cape: Key Features

- Leverage Beagle Bone Black for data processing (1GHz CPU)
- Multi-channel
  - 8, up to 16 with Cape stacking
- All-in-one solution for power measurement, power control, and temperature measurement
- Flexible / Evolutive
  - Extension connector for use with other HW than BBB
  - New probes can be designed, w/o HW change required on ACME cape
- Complete Open Source SW Suite
- Standard ACME Probe Connector (free of charge)
- Low-cost

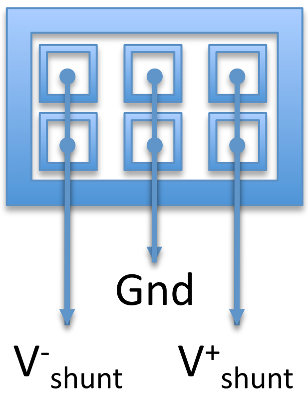
ACME Cape: Key Decisions

- Probes include the ADC for best accuracy
  - No more long wires between shunt and ADC
- Use TI INA226 & TMP435 components featuring upstream Linux drivers
- Flexible Client/Server SW Architecture
  - To handle any sort of usage (local/remote/simultaneous/...)
- Define a standard low-cost power measurement connector (free of charge) and provide power probes following this standard
- Scalable HW design to reduce cost

ACME Cape: Standard PM Connector

- Objectives:
  - Provide a standard way to get development board ready for power measurements
    - No more HW modification
  - Get rid of proprietary / ad hoc solutions
    - Today: new board = new HW tweaks = no reuse
  - Ultra low-cost, low footprint, easy integration for board manufacturers
  - Open standard / free of charge (no licensing fee)

- Our solution: the ACME Probe Connector
  - Leveraging good old world-famous HE10 connector
  - Handle up to 6A (3A single line)
  - Shunt resistor may or may not be populated on the PCB
    - HE10 ACME probes available with or without shunt resistor
  - Proof of concept demonstrated on SAMA5D3-XPlained board



ACME Cape vs NI-DAQ

Feature	NI-DAQ NI USB-6002	ACME Solution
ADC Resolution Sample rate Accuracy	16-bit 6 Ksamples/s 6 mV	16-bit 7 Ksamples/s 2.5 uV
Channels	8 (only 4 for power meas. (U + I))	8
Power Probes (incl. shunt) USB Power Probe Jack Power Probe Standard Power Connector	No No No No	Yes Yes Yes Yes
Temperature Probes	No	Yes
Remote Power Control	No (only I/O avail.)	Yes
Visualization App.	Yes (proprietary, MS Windows)	Yes (multi-platforms)
Remote Control App.	Yes (LabVIEW)	Yes
Automation	Yes (LabVIEW)	Yes (scripting)
Open Source drivers & app.	No	Yes!

ACME Cape: Status

- First batch of capes and probes built & fully operational:
  - 20x capes
  - 40x HE10 probes
  - 20x Jack probes
  - 20x USB probes
  - 20x temperature probes

- Version 0.1 of SW Suite available, including:
  - Server (daemon) running on Beagle Bone Black
  - Pseudo real-time visualization browser application
  - Pseudo real-time visualization Qt5 application
  - Automation tools
  - Dedicated web page: www.baylibre.com/acme
  - Feedback e-mail: acme@baylibre.com

- Opening beta testing /feedback collection phase
  - Recruiting beta testers, please apply! ☺

ACME Cape: What's next?

- Beta testing /feedback collection phase
  - We need you! ☺
  - acme@baylibre.com
- Continue SW suite development
- Prepare HW rev. B
  - Reduce production cost towards mass production
- Prepare Kickstarter funding for larger production – Early 2015
- Get the ACME probe connector adopted by board manufacturers
- Finally become your preferred solution for power measurements ☺

Demo

Multi-channel power measurement

Q & A

Thank you!